

The Globular Clusters in M87: A Bimodal Colour Distribution ¹

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Abstract

We present V and I photometry for ~ 150 globular clusters with $20 < V < 27$ ~ 2.5 arcmin from the centre of M87, the cD galaxy in the Virgo cluster. The data were acquired with the Hubble Space Telescope which, with effective resolution 0.1 arcsec, allows us for the first time to distinguish between globular clusters and most background galaxies on the basis of morphology, and to obtain accurate photometry even at faint magnitudes. The $(V - I)$ distribution of the clusters is clearly bimodal, implying a corresponding bimodality in the metallicity distribution, with peaks at $[\text{Fe}/\text{H}] \approx -1.5$ and -0.5 . We also find that the brightest clusters are predominantly metal poor, while the fainter clusters are divided roughly equally between metal poor and metal rich. Our sample is essentially complete to $V \approx 25$, a full magnitude past the expected peak of a “universal” luminosity function, and the observed luminosity function is well represented by the standard gaussian distribution with $\langle M_V \rangle = -7.2$ and $\sigma = 1.4$.

Key words: galaxies: star clusters — galaxies: individual: M87

1. Introduction

Detailed studies of globular cluster systems in various types of galaxies are beginning to yield important clues regarding the formation of both the globular clusters and their host/parent galaxies. (For recent reviews see Harris 1991; 1995). In particular, the large populations of clusters often associated with elliptical galaxies have prompted the suggestion that clusters form during mergers of the subunits which may have gone into building the galaxies (cf. Ashman and Zepf

1992). This possibility has gained popularity recently in light of the discovery of objects which appear to be young globular clusters in NGC 1275, NGC 3597, NGC 7252, and He 2-10, all disturbed galaxies which have probably undergone recent mergers (Holtzman *et al.* 1992; Lutz 1991; Whitmore *et al.* 1993; Conti and Vacca 1994). However, since field stars would also form during mergers, such a scenario may have trouble accounting for the higher specific frequencies of clusters in many elliptical galaxies (cf. Harris 1995).

One signature of a merger origin for globular clusters, or indeed of any scenario in which clusters form in successive bursts, might be a bimodal or multimodal metallicity distribution (Zepf and Ashman 1993), which should manifest itself as a bimodal or multimodal colour distribution in indices such as $(B - I)$ or $(V - I)$. Zepf and Ashman show histograms of metallicity for globular clusters in two galaxies, NGC 4472 and NGC 5128, both of which are bimodal. NGC 5128 is a peculiar elliptical galaxy with a dust lane and a jet, and NGC 4472 is an E/S0 shell galaxy with CO emission. On the other hand, Ajhar, Blakeslee and Tonry (1994) present $(V - I)$ histograms for globular clusters associated with 10 elliptical and S0 galaxies in the Virgo and Leo clusters and find that, while the histograms differ substantially from galaxy to galaxy, none shows evidence for bimodality.

M87 (NGC 4486), the central giant elliptical in the Virgo cluster, was not among the galaxies studied by Ajhar *et al.* because its high specific number of clusters made it unrepresentative of elliptical galaxies in general. Its jet also makes it atypical. However, understanding the origin of its prodigious population of clusters, whether primordial, by accretion of companion galaxies with their

attendant clusters, or in more recent episodes of cluster formation in mergers or cooling flows, is an important quest.

Recently, Lee and Geisler (1993) have used Washington system photometry to estimate metallicities for about 400 M87 clusters at radii $\sim 1 - 4$ arcmin. They find a broad distribution of values with a mean of $[\text{Fe}/\text{H}] \approx -0.9$. Couture, Harris and Allwright (1990) present a $(V - I)$ histogram for a sample of 106 M87 globular cluster candidates brighter than $V \sim 23.4$. They also find a broad distribution of colours, with $\langle V - I \rangle \approx 1.0$, which they estimate corresponds to $[\text{Fe}/\text{H}] \approx -1.0$. Neither of these studies reveals evidence for bimodality in the metallicity distribution.

In this paper we present V and I photometry for a sample of ~ 150 globular clusters with $V < 27$, observed with the Hubble Space Telescope (HST). HST enables us to obtain accurate colours even at faint magnitudes, and is unique in allowing us to distinguish between globular clusters and most background galaxies on the basis of morphology, and thus to be assured of a relatively uncontaminated sample. Our observations and sample selection are described in Section 2, and our results are presented in Section 3.

2. Observations

Our study is based on images of a field located ~ 2.5 arcmin from the centre of M87, obtained with HST's refurbished Wide Field Camera (WFC-2) on 1994 August 4, as part of the Medium Deep Survey Key Project (cf. Griffiths *et al.* 1994). The images were acquired in parallel mode, in fine lock. The F814W (\sim Cousins I) and F606W (\sim Cousins V) filters were used. Two 1000 second exposures were

obtained with each. The gain is $7.0\ e^-/\text{ADU}$, and the readnoise is $7\ e^-$. The image scale for the WFC-2 is $0.10\ \text{arcsec/pixel}$. Adopting a distance modulus for M87 of 31.0 based on recent observations of Cepheids (Pierce *et al.* 1994, Freedman *et al.* 1994) gives a pixel size of 8.7 pc. A typical globular cluster would have core radius less than 10 pc and tidal radius of order 50 pc; in our relatively shallow exposures only the cores are visible, and the clusters are therefore unresolved. Eliminating the unexposed edges of each of the three 800×800 pixel WFC-2 chips gives a field of view with total area $4.7\ \text{arcmin}^2$. (To maintain homogeneous selection criteria, the Planetary Camera image, with smaller scale and area only $0.3\ \text{arcmin}^2$ was not used.)

The individual images in each colour were coadded using an IRAF package developed by K. Glazebrook. In order to remove cosmic ray events, the smallest of the two pixel values at each position in each chip was adopted. For our 1000 second exposures, only about 2% of cosmic ray events should escape elimination by this process, affecting only 0.03% of the pixels (WFPC-2 Instrument Handbook version 2.0). Since the individual frames are not dithered, hot pixels could not be removed by coadding. Instead, they were identified and flagged using software kindly provided by N. Tanvir. Figure 1 shows a 255×255 pixel subsection of the coadded F606W Chip 3 image.

2.i. Object detection and photometry

Objects were detected automatically using the Cambridge APM software (Irwin 1985). The adopted detection threshold was 1.5 times the standard deviation of the background, which corresponds to a surface brightness in I_{814} of $23\ \text{mag arcsec}^{-2}$. In order to eliminate cosmic ray residuals, chip defects, noise

spikes, and very faint unresolved galaxies, a minimum diameter of 0.3 arcsec was also imposed.

Magnitudes were measured using aperture photometry with an aperture of radius 2 pixels. The full radius of the point spread function is ~ 25 pixels (Holtzman *et al.* 1995), so an aperture correction was required to derive total magnitudes. This was determined to be 0.38 mag from observations of isolated compact objects. Clearly any resolved galaxies would require larger aperture corrections, depending on their surface brightness profiles, and their magnitudes may be underestimated here. This does not pose a problem for us since our only interest in the galaxies is in eliminating them from our sample. The adopted sky brightness for each object was the mode in an annulus at radii 30-35 pixels. Photometric zero-points are 21.67 for the F814W filter, and 22.84 for the F606W filter (Holtzman *et al.* 1995).

The instrumental HST magnitudes were converted to Johnson-Cousins magnitudes (V, I) using the relations

$$I = I_{814} + 0.001 - 0.126(V_{606} - I_{814}) + 0.047(V_{606} - I_{814})^2$$

and

$$V = V_{606} - 0.033 + 0.252(V_{606} - I_{814}) + 0.004(V_{606} - I_{814})^2$$

These include conversions from space-based to ground based WFC-2 magnitudes (Holtzman *et al.* 1995) and from ground-based WFC-2 magnitudes to the Johnson-Cousins system (Harris *et al.* 1991). The V conversion involves a $(B - V)$ colour term for which we adopted the relation $(V - I) = 1.29(B - V) + 0.12$ from Couture *et al.* (1990). This is only valid for M87 globular clusters, and there is significant

scatter about this relation, which will introduce uncertainties in the conversion. Further uncertainties are introduced because the Harris *et al.* transformations are themselves based on observations of individual dwarfs, and may not therefore be valid for globular clusters, where the integrated light tends to be dominated by giants. The transformations are therefore tentative, and we present our results in both the HST instrumental and Johnson-Cousin systems. The difference between the HST and Johnson-Cousins I magnitudes is less than 0.08 mag. In V , the difference ranges from 0.05 mag at $(V_{606} - I_{814}) = 0.4$ to 0.25 mag at $(V_{606} - I_{814}) = 1.1$. A colour-magnitude diagram for 238 objects with $V_{606} < 27$ is shown in Fig. 2. Errors range from ± 0.02 mag at $V_{606} = 22.5$ to ± 0.05 at $V_{606} = 23.5$.

2.ii. *Elimination of stars and galaxies*

We now wish to eliminate stars and galaxies from our sample. We begin by restricting our sample to objects with colours consistent with those of globular clusters. Referring to Fig. 5 of Couture *et al.* (1990), reasonable limits are $0.6 < (V - I) < 1.4$, which corresponds to $0.47 < (V_{606} - I_{814}) < 1.08$. Adding ± 0.1 to account for scatter in the observed colours, we make our initial selection at $0.37 < (V_{606} - I_{814}) < 1.18$. These limits are indicated with dashed lines in Figure 2. This gives a sample of 187 globular cluster candidates.

We can estimate the expected number of foreground stars and background galaxies using the Medium Deep Survey database. A study of Galactic stars in 13 high-latitude WFC-2 fields (Santiago *et al.* 1995) indicates that we should expect about one star per magnitude bin per field, so at $20 < V < 26$, about six stars altogether, or two per chip. Since the cores of the globular clusters are unresolved, it is not possible to distinguish them from stars on the basis of the appearance of

the images. However the fraction of stars expected is only $\sim 4\%$ of the final sample, and this level of contamination will not affect any of our results significantly.

Unlike stars, most background galaxies can be eliminated by visual inspection of the images. Edge-on or elongated galaxies and lumpy or low surface brightness objects are easily distinguished from globular clusters as can be seen in Figure 1. We identified 40 galaxies among the 187 globular cluster candidates. This is consistent with the number expected based on the same 13 high latitude Medium Deep Survey fields discussed above. Eliminating these galaxies from our sample leaves a total of 147 objects.

Distant early-type galaxies are not morphologically distinguishable from globular clusters and may still contaminate our sample. However, ellipticals and compact galaxies account for only about 20% of the Medium Deep Survey galaxy population brighter than $I = 22.0$ ($V \approx 24$) (Griffiths *et al.* 1994) and even less than that at fainter magnitudes and with $0.6 < (V - I) < 1.4$ (Driver *et al.* 1995, Glazebrook *et al.* 1995). Thus, these objects should constitute less than 8% of the final sample, giving a total contamination by stars and galaxies of less than 12%.

3. Results

3.i. Colour distributions

Figure 3a shows a histogram of $(V_{606} - I_{814})$ values for the 187 globular cluster candidates selected by colour, and for the final sample of 147 globular clusters. The objects identified as galaxies tend to lie in the wings of the distribution. Both histograms are clearly bimodal, with peaks at $(V_{606} - I_{814}) \approx 0.6$ and 0.8.

Figure 3b shows a histogram for the final sample of 147 globular clusters, with magnitudes transformed to the Johnson-Cousins system. Superposed is the histogram from Fig. 5 of Couture *et al.* for 106 M87 clusters with $V < 23.4$. There appears to be a systematic offset in the sense that our histogram is shifted bluewards by ≈ 0.15 mag. This is probably due to uncertainties in our transformation from the HST to Johnson-Cousins magnitudes, discussed above. Given that the transformation is based on observations of dwarfs, not globular clusters, and that there is a $(B - V)$ term which must be approximated by a relation which is known to have significant scatter, a systematic uncertainty of 0.15 mag in $(V - I)$ would not be unlikely. The important feature of our histogram is its bimodality, and this is not affected by the transformation.

As discussed above, such bimodality has been observed in the globular clusters systems of several other galaxies. However, it has not been noted in previous studies of the M87 cluster system. As Couture *et al.* point out, studies using $(B - V)$ or $(g - r)$ indices would not be expected to show such bimodality because the span of wavelengths is too narrow. However, their $(V - I)$ histogram might be expected to show bimodality. To compare our results directly with theirs, Fig. 3c shows a histogram for the 76 brightest clusters in our sample, with $V < 23.5$, shifted redwards by 0.15 mag. Again, the histogram from Couture *et al.* is superposed. The latter does show some suggestion of bimodality with peaks similar to ours, although it is also consistent with a single broad distribution. The errors in Couture *et al.* 's photometry are ± 0.2 mag at $V = 21.5$ and ± 0.3 mag at $V = 22.5$. In comparison, our errors are an order of magnitude less: ± 0.02 mag at $V = 22.5$ and ± 0.05 mag at $V = 23.5$. It is likely that their errors are too large to fully

resolve the bimodality evident in our sample. Lee and Geisler (1993) present a histogram of values of $[\text{Fe}/\text{H}]$ for M87 globular clusters, derived from Washington system narrow band photometry. They too find a broad distribution of values ranging from $[\text{Fe}/\text{H}] \approx -2$ to 0.5 . They estimate their errors in the photometric index to be ± 0.06 , which translates into an error in $[\text{Fe}/\text{H}]$ of ± 0.15 dex. Again, these uncertainties may be too large to resolve a bimodality.

A difference in colour among clusters could in principle be due to a difference in age, in the sense that younger clusters would have systematically bluer colours. However as Couture *et al.* note, $(V - I)$ colours are relatively insensitive to age: an age difference of, for example, 2 Gyr would not affect $(V - I)$ significantly. The difference is far more likely to be due to a difference in metallicity. Using the relation given by Couture *et al.* between colour and metallicity, we estimate that the blue peak in Fig. 3c corresponds to $[\text{Fe}/\text{H}] \approx -1.5$, and the red peak to $[\text{Fe}/\text{H}] \approx -0.5$. These values are consistent with the peaks at -1.7 and -0.5 found by Zepf and Ashman (1993) in NGC 4472, and are slightly more metal poor than those in NGC 5128, at -1.2 and -0.1 . Our results therefore suggest that there were at least two distinct episodes of cluster formation in M87, or that clusters were accreted from parent galaxies with different metallicities.

Interestingly, there appear to be relatively more metal poor (bluer) clusters in our brighter sample compared to our fainter sample. Figure 3d shows histograms for the clusters with $V < 23.5$ ($N = 76$), and with $23.5 < V < 25$ ($N = 64$). Among the bright clusters, the blue peak is dominant, whereas among the fainter clusters, the red peak is dominant. Specifically, for the bright sample, 72% of the

clusters have $(V - I) < 0.9$ while 28% have $(V - I) > 0.9$. For the fainter clusters, the fractions are 42% and 58% respectively.

This trend is also present in the sample prior to converting the instrumental magnitudes to the Johnson-Cousins system, and is therefore not the result of any systematic uncertainties in the conversion. Nor is it a result of any colour-dependent incompleteness. As Fig. 4 (below) illustrates, our sample should be complete to $V = 25$. If, however, we adopt a more conservative completeness limit at $V = 24$ and repeat the above analysis, dividing the sample at $V = 22.8$, we still find the same trend. Finally, we ask whether the trend could be the result of contamination of our sample by faint, red, unresolved galaxies. MDS results for a sample of “compact” and elliptical galaxies with $V < 23$ show no systematic shift redwards at fainter magnitudes in the range of colours considered here. Morphological classifications at $V > 23$ were not possible, however we estimate above that contamination of our sample by compact galaxies indistinguishable from globular clusters is about 8%, or about 12 galaxies. If we adopt the extreme assumption that all 12 possible interlopers are faint and red and remove them from the sample accordingly, then the fraction of blue and red clusters in the fainter sample changes from 42% and 58%, to 52% and 48%. The ratios for the bright clusters remain unchanged. Thus, even in this case, the trend of brighter clusters being predominantly blue or metal poor compared to the fainter clusters persists.

Such a trend has never before been noted in any galaxy. The likely reason for this is that to resolve it requires very accurate photometry at faint magnitudes. The peaks in our colour distribution are separated by only 0.2 mag, and the median colours of the bright and faint samples differ only by 0.1 mag.

If real, the trend illustrated in Fig. 3d suggests that lower metallicity environments favour the formation of more massive clusters, while higher metallicity environments tend to produce smaller clusters. Harris and Pudritz (1994) present a model for cluster formation in which clusters form in the cores of supergiant molecular clouds, with mass proportional to the size of the progenitor cloud. If at a later, more chemically enriched epoch, the progenitor clouds had been broken into smaller pieces by tidal forces or through cloud-cloud collisions, then one would expect the more metal rich clusters to be smaller. Indeed, a somewhat analagous trend is seen in the Large Magellanic Cloud, where none of the (more metal rich) younger clusters are as massive as the oldest (more metal poor) clusters. (Even if the younger clusters are currently as massive as the oldest clusters, they will lose a significant fraction of their mass through stellar evolution and evaporation. Thus, their predicted final masses are smaller than the masses currently observed among the oldest clusters.)

3.ii. *Luminosity functions*

Figure 4 shows a luminosity function for the 147 globular clusters in our final sample. Superposed is a gaussian distribution with $\langle V \rangle = 23.8$ ($\langle M_V \rangle = -7.2$), and $\sigma = 1.4$, the values given by Flemming *et al.* (1995) for the M87 globular cluster system, normalized to the total number of clusters with $V < 24$ ($N = 100$). At this is the magnitude we expect our sample to be complete, based on results from Santiago *et al.* (1995) who make use of simulations of HST images with various signal-to-noise ratios to determine completeness as a function of magnitude in images similar to these. The gaussian function matches the data very well for $V < 25$. Fainter than this our sample rapidly becomes incomplete.

Integrating the gaussian distribution implies a surface density of 38 clusters per square arcmin. Harris (1986) derives a surface density profile for the M87 globular cluster system which implies 20 clusters per square arcmin at a radius of 2.5 kpc. His estimate of the limiting magnitude of his sample is uncertain, but corresponds roughly to $V = 23.5$. To this limit we observe 16 clusters per square arcmin, in good agreement with Harris' value. Thus, we confirm his result that the globular cluster system of M87 is less centrally concentrated than the underlying galaxy.

4. Conclusions

We have presented accurate V and I photometry for ~ 150 globular clusters in M87. We find a colour distribution which is clearly bimodal, with peaks corresponding to metallicities of $[\text{Fe}/\text{H}] \approx -1.5$ and -0.5 . Among the brighter clusters, with $20 < V < 23.5$, metal poor clusters constitute 72% of the sample. Among the fainter clusters, with $23.5 < V < 25$, metal poor clusters constitute only 42% of the sample. These results suggest that there were at least two distinct episodes of cluster formation in M87, or that the clusters were accreted from parent galaxies with different mean metallicities. They suggest further that metal poor environments may favour the formation of more massive clusters, while less massive clusters form preferentially in more metal rich environments. Finally, our sample is complete to $V \approx 25$, a full magnitude past the expected peak of a “universal” luminosity function, and we find that our observed luminosity function is well represented with the standard gaussian function, with $\sigma = 1.4$.

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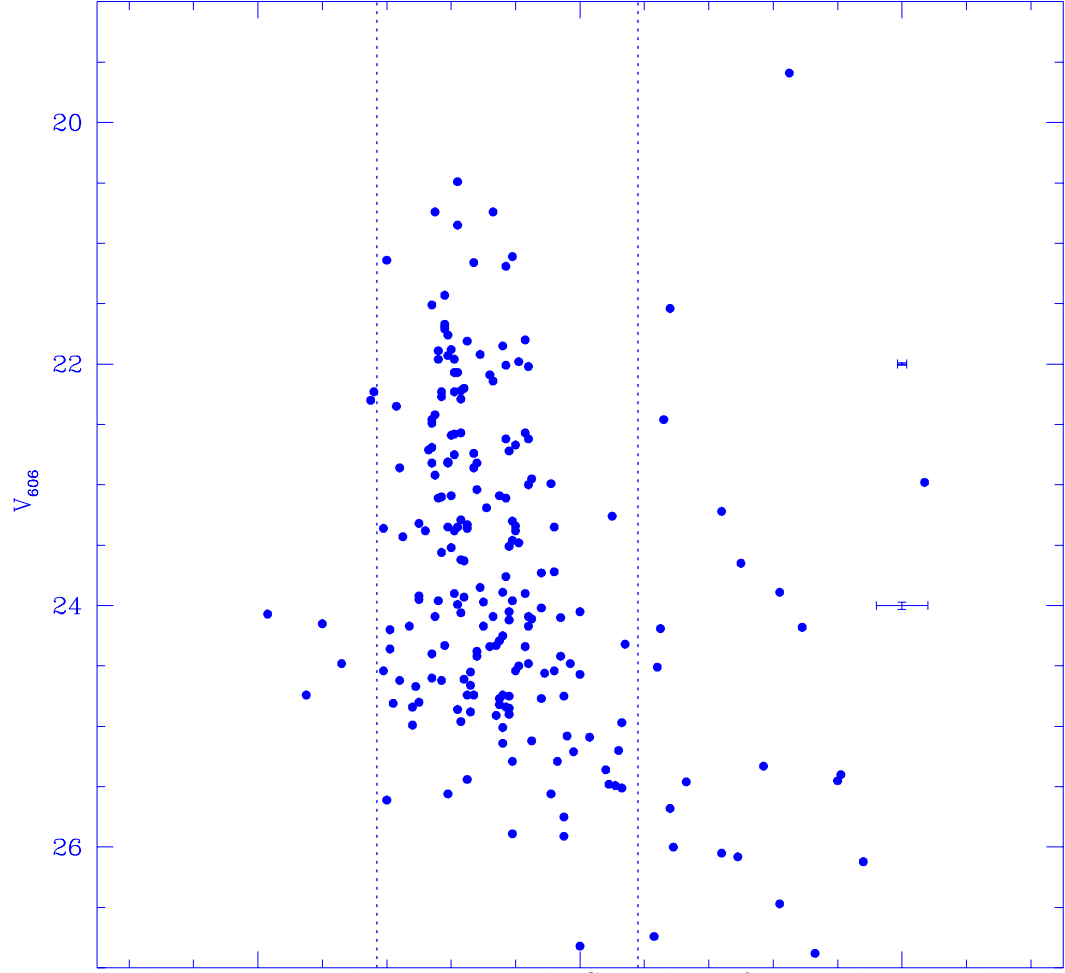
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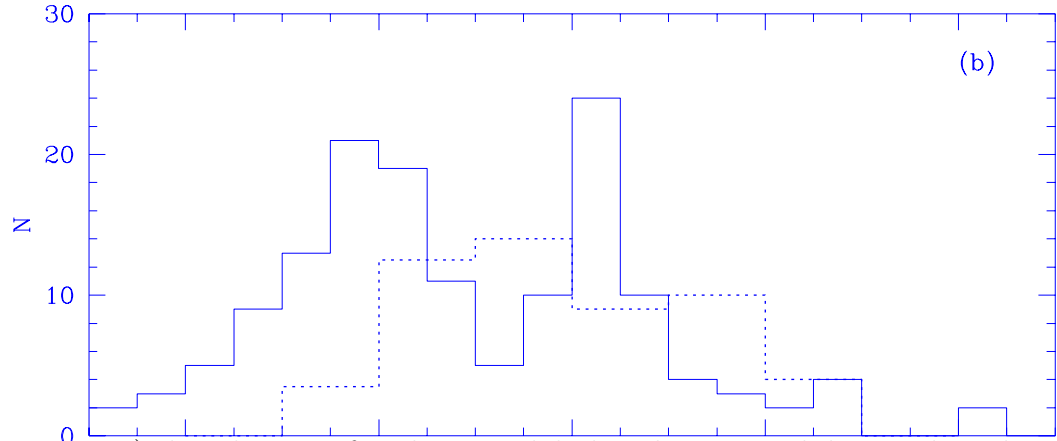
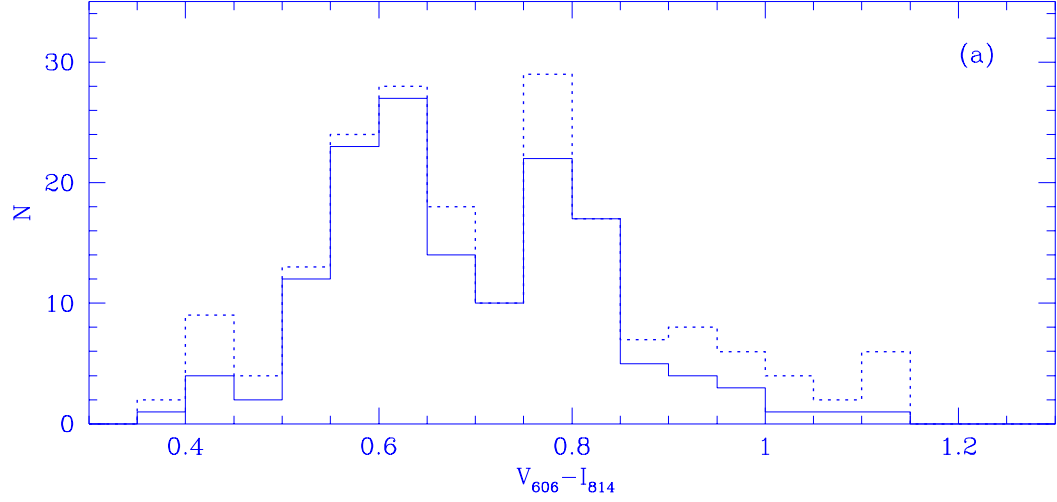
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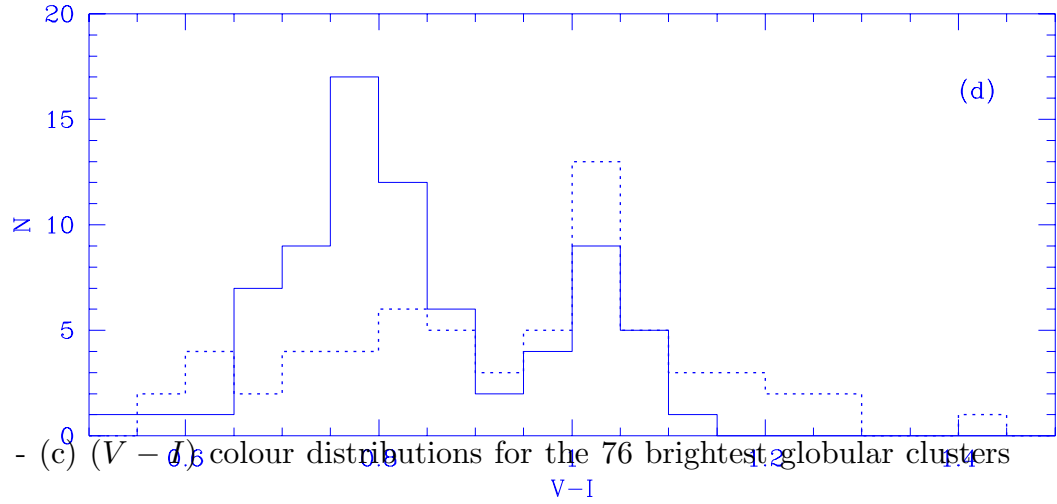
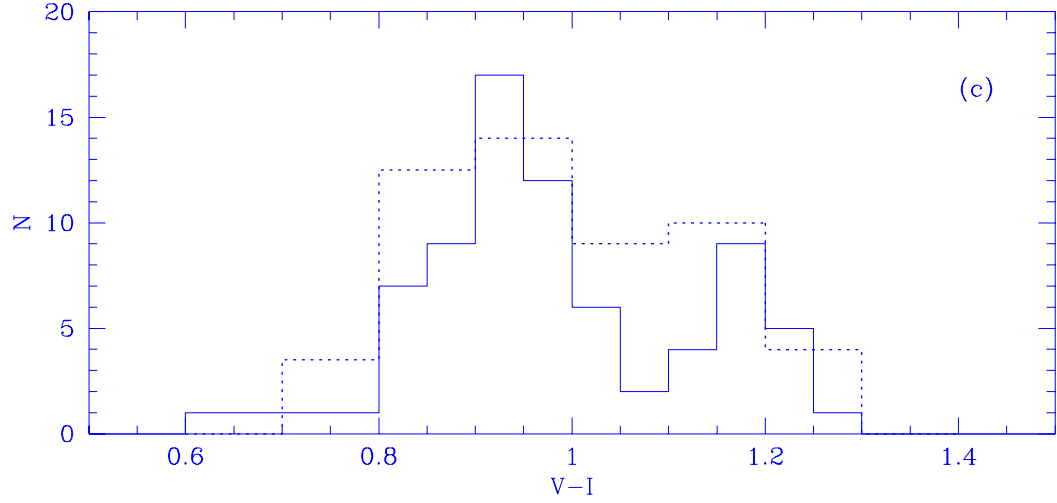
2- Colour-magnitude diagram with instrumental HST colours for 238 objects. The vertical dashed lines indicate the limits of $(V_{606} - I_{814})$ for globular clusters in M87, as discussed in Section 2.ii. Representative Poisson error bars are shown. No reddening corrections have been applied.

Figure Captions

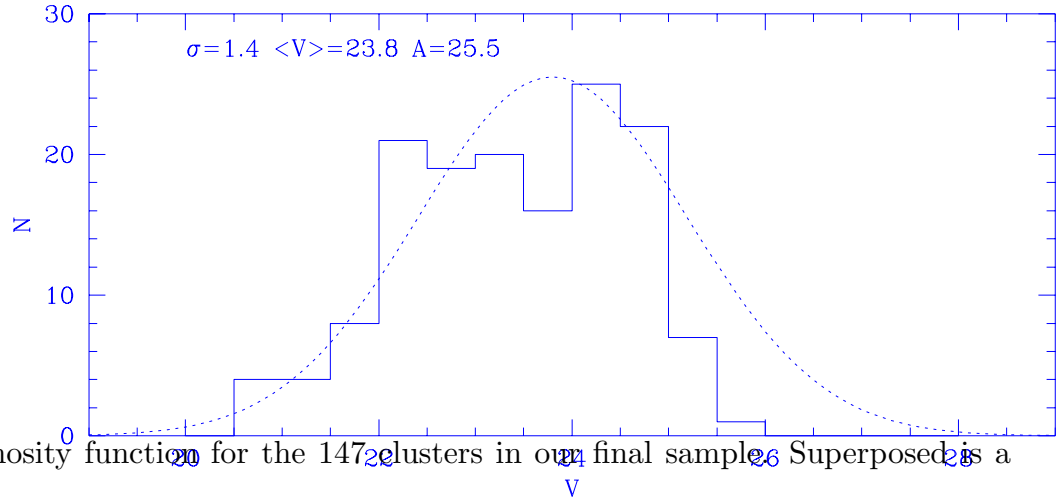
surface brightness.



3- (a) $(V_{606} - I_{814})$ distributions for the 187 globular cluster candidates selected by colour (dotted line), and for the final sample of 147 globular clusters, from which galaxies have been eliminated on the basis of morphology (solid line). (b) $(V - I)$ colour distributions for the 147 globular clusters in our final sample (solid line), compared with the distribution from Couture *et al.* for 106 M87 clusters with $V < 23.5$ (dotted line). Our distribution appears to be shifted bluewards by ≈ 0.15 mag.



3 (cont.) - (c) $(V-I)$ colour distributions for the 76 brightest globular clusters ($V < 23.5$) in our final sample (solid line), compared with that from Couture *et al.* (1990). Our histogram has been reddened by 0.15 mag to bring it into coincidence with that of Couture *et al.* (d) Histograms for the 76 brightest clusters ($V < 23.5$) (solid line) and 64 fainter clusters ($23.5 < V < 25$) (dotted line) in our final sample. No colour offsets have been applied.



4- Luminosity function for the 147 clusters in our final sample. Superposed is a gaussian distribution with $\langle V \rangle = 23.8$ ($\langle M_V \rangle = -7.2$) and $\sigma = 1.4$, normalized to the number of clusters with $V < 24$ ($N = 100$).